

| REPORT DOCUMENTATION PAGE | | | Form Approved OMB No. 0704-0188 | |
|---|---|--|---|---|
| Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503. | | | | |
| 1. AGENCY USE ONLY (Leave blank) | | 2. REPORT DATE 2005 | | 3. REPORT TYPE AND DATES COVERED Journal Article-Sports Medicine |
| 4. TITLE AND SUBTITLE Running Performance Differences between Men and Women (An Update) | | | 5. FUNDING NUMBERS | |
| 6. AUTHOR(S) C.N. Cheuvront; R. Carter; K.C. DeRuisseau; R.J. Moffatt | | | | |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Thermal & Mountain Medicine Division U.S. Army Research Institute of Environmental Medicine Kansas Street Natick, MA 01760-5007 | | | 8. PERFORMING ORGANIZATION REPORT NUMBER MISC 05-02 | |
| 9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Same as #7 above | | | 10. SPONSORING / MONITORING AGENCY REPORT NUMBER | |
| 11. SUPPLEMENTARY NOTES | | | | |
| 12a. DISTRIBUTION / AVAILABILITY STATEMENT Distribution is unlimited. | | | 12b. DISTRIBUTION CODE | |
| 13. ABSTRACT (Maximum 200 words) More than a decade ago it was reported in the journal Nature that the slope of improvement in the men's and women's running records, extrapolated from mean running velocity plotted against historical time, would eventually result in a performance intersection of the sexes across a variety of running distances. The first of these intersections was to occur for 42000 m before the 21st century. Most of the error in this prediction is probably explained by the linear mathematical treatment and extrapolation of limited performance data, since inclusive world record setting running performances for women before and after 1985 results in a non-linear data fit. The reality of early, disproportionate improvements in women's running that gave the appearance of an impending convergence with men is best explained by an historical social sports bias. Women's times have now reached a plateau similar to that observed for men at comparative performance milestones in the marathon. Gender differences at distances from 100 – 10000 m show similar trends. The remaining gender gaps in performance appear biological in origin. Success in distance running and sprinting is determined largely by aerobic capacity and muscular strength, respectively. Because men possess a larger aerobic capacity and greater muscular strength, the gap in running performances between men and women is unlikely to narrow naturally. | | | | |
| 14. SUBJECT TERMS gender, world records, sprinting, endurance, biology | | | 15. NUMBER OF PAGES 8 | |
| | | | 16. PRICE CODE | |
| 17. SECURITY CLASSIFICATION OF REPORT Unclassified | 18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified | 19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified | 20. LIMITATION OF ABSTRACT Unclassified | |

Running Performance Differences between Men and Women

An Update

Samuel N. Cheuvront,¹ Robert Carter III,¹ Keith C. DeRuisseau² and Robert J. Moffatt³

1 US Army Research Institute of Environmental Medicine, Natick, Massachusetts, USA

2 University of Florida, Gainesville, Florida, USA

3 Florida State University, Tallahassee, Florida, USA

Abstract

More than a decade ago it was reported in the journal *Nature* that the slope of improvement in the men's and women's running records, extrapolated from mean running velocity plotted against historical time, would eventually result in a performance intersection of the sexes across a variety of running distances. The first of these intersections was to occur for 42 000m before the 21st century. Most of the error in this prediction is probably explained by the linear mathematical treatment and extrapolation of limited performance data, since including world record-setting running performances for women before and after 1985 results in a non-linear data fit. The reality of early, disproportionate improvements in women's running that gave the appearance of an impending convergence with men is best explained by an historical social sports bias. Women's times have now reached a plateau similar to that observed for men at comparative performance milestones in the marathon. Sex differences at distances from 100 to 10 000m show similar trends. The remaining sex gaps in performance appear biological in origin. Success in distance running and sprinting is determined largely by aerobic capacity and muscular strength, respectively. Because men possess a larger aerobic capacity and greater muscular strength, the gap in running performances between men and women is unlikely to narrow naturally.

The differences in running performances between men and women have attracted considerable attention over the last 30 years. The foundation for this interest is in part rooted in the extreme contrast between women's historical and present-day sports participation (table I). The first Olympic Games, of

1896, did not include a single female athlete. A century later, 36% of >10 000 athletes competing in the XXVI Olympic Summer Games were women.^[1] The marathon is specifically a fine example of the coming of age in women's distance running. Early social sports biases precluded women in the US

Table I. Timeline and commentary on women's historical participation in distance running^[2,5]

| Timeline | Commentary |
|----------|--|
| 1928 | Several women collapse after finishing the Olympic 800m. Women are considered too fragile for distance running and the event is banned |
| 1960 | The women's Olympic 800m is reinstated |
| 1972 | A first women's Olympic 1500m is run. Eight women 'legally' run the Boston Marathon |
| 1984 | A first women's Olympic marathon is run |
| 1998 | The Boston Marathon is host to 3500 women runners. The New York City Marathon reports 9000 women entrants |

from 'legally' competing at 42 000m until 1972.^[2] Similarly, the marathon was not added as an Olympic event for women until 1984. Yet despite these delays, <11 minutes currently separates the best men's and women's marathon performances.^[3,4]

The progression of world record running performances for women initially improved at a faster rate than for men during the same historical time frames (figures 1, 2 and 3). Comparative analyses of these performances inspired some to conclude that women would outrun men sooner^[6] or later.^[7] In fact, the first running performance intersection between the sexes was to occur for 42 000m just before the 21st century.^[6] Although ultimate running performance predictions^[8] and even sex comparisons^[9] have been examined before, the interpretation of an impending intersection^[6] fostered renewed scientific curiosity and controversy.^[1,9-13] The subject also made an impression on the public. According to a 1996 survey of Americans, 66% believed that top women athletes would one day outperform their male counterparts.^[14] It appears, however, that the reality of disproportionate improvements in women's running is best explained by an historical social sports bias.^[1,9,10] Changes in the societal acceptance of women's distance running (table I) have resulted in more opportunities for training and competing.^[9,15] Present-day running

performances for women have now reached a plateau similar to that for men^[10] (figures 1–3), and the remaining sex differences appear to be of biological origin.

The primary purpose of this brief review is to update the literature comparing historical world record running performances for men and women to include sprinting events (100–400m) and a glimpse at the future for all distances from 100 to 42 000m. A secondary purpose is to provide a concise summary explanation for the present-day performance differences that includes social and biological influences.

1. Performance Differences: Past and Present

Sparling et al.^[10] concluded that distance running performances for women have reached a plateau based on an analysis of world rankings from 1980 to 1996. The performance differences between the sexes were 10–13% when comparing the top 50 times for men and women in running events from 1500 to 42 000m just prior to the turn of the century. Figures 1 and 2 illustrate convergent trends for world best performances at those distances before 1980 that stabilised between 1985 and 2004 and range from 8% to 14% today (table II). For the marathon (figure 1), women improved by 4% between 1985 and

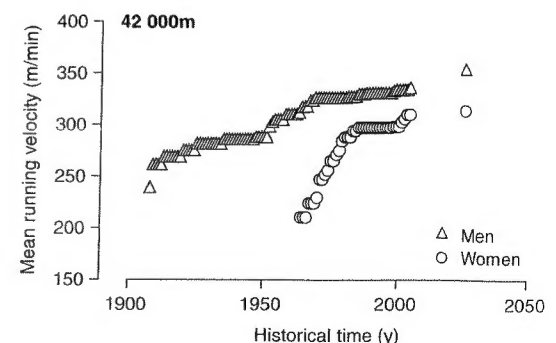


Fig. 1. Progression in men's and women's world record running performances for 42 000m between 1908 and 2004 with predictions for 2028 (see appendix for more details).

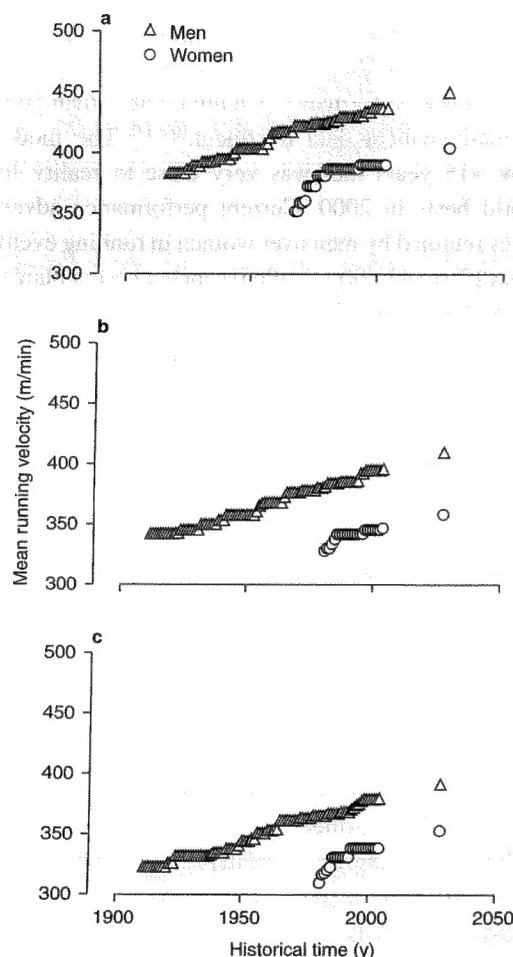


Fig. 2. Progression in men's and women's world record running performances for: (a) 1500m (1917–2004); (b) 5000m (1912–2004); and (c) 10000m (1911–2004), with predictions for 2028 (see appendix for more details).

2004, while men improved by only 1.8%. Viewed more closely, the improvement for women included a 13-year plateau (1985–1997) at a running velocity of 297.7 m/min, followed by a marked increase in mean running velocity to 310.2 m/min over the last 6 years (figure 1). Men achieved a similar accomplishment for a similar performance milestone. From 1935 to 1953, marathon performances for men improved by 5.5%. From 1935 to 1946 they, too, experienced a 13-year plateau for a 286.3 m/min

running velocity, followed by an improvement to 303.1 m/min in the 6 subsequent years (figure 1).

Paula Radcliffe's 2003 world record in the marathon (310.2 m/min) has specifically received enormous attention because it represents a 113-second improvement over her previous 2002 mark, which itself was 89 seconds faster than the former record (total improvement of 202 seconds).^[3] Few recognise that improvements of this magnitude have

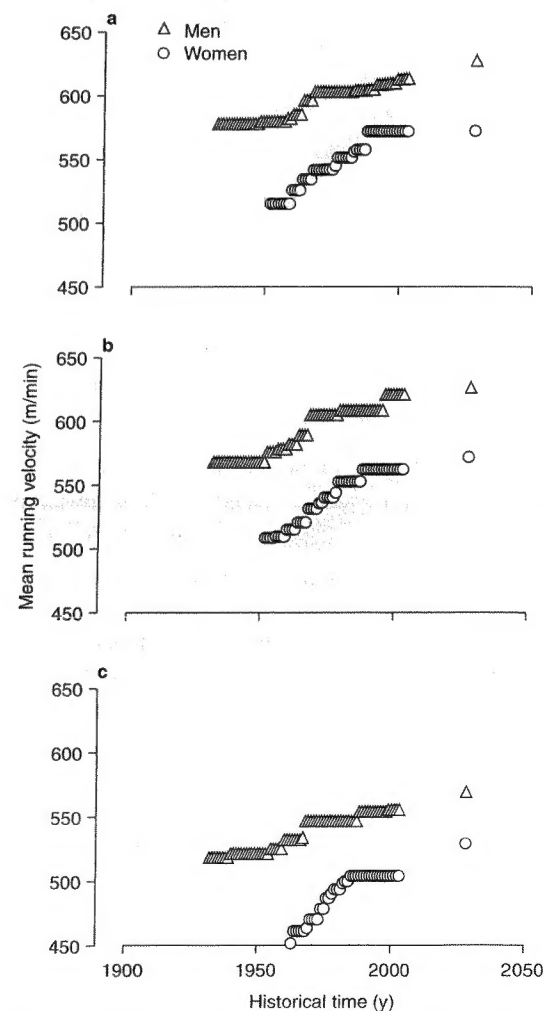


Fig. 3. Progression in men's and women's world record running performances for: (a) 100; (b) 200; and (c) 400m, between 1932 and 2004 with predictions for 2028 (see appendix for more details).

Table II. Sex differences in world record running performances for 100–42 000m as of October 2004^[3,4]

| Distance (m) | Time (h:min:sec.hundredth) | | Difference (%) ^a |
|-----------------|----------------------------|------------|--------------------------------|
| | men | women | |
| 100 | 9.78 | 10.49 | 7.3 ^b |
| 200 | 19.32 | 21.34 | 10.5 |
| 400 | 43.18 | 47.60 | 10.2 |
| 1 500 | 3:26.00 | 3:50.46 | 11.9 |
| 5 000 | 12:37.35 | 14:24.68 | 14.1 |
| 10 000 | 26:20.31 | 29:31.78 | 12.1 |
| 42 000 | 2:04:55.00 | 2:15:25.00 | 8.4 |

a Percentage differences calculated as [(women's time – men's time)/women's time] × 100.

b There is some controversy surrounding this women's record (10.49).^[3] If the second fastest time from the 1988 US Olympic Trials is used (10.61), the difference is (7.8%).

also been observed before for men. For example, Sergey Popov bettered Jim Peters' 1954 world marathon record by 142 seconds in 1958, running 305.1 m/min. In 1967, Derek Clayton ran 324 m/min to lower the world best by 144 seconds, only to lower it again by an additional 63 seconds in 1969 (total improvement of 207 seconds).^[3]

Performance differences at distances from 1500 to 10 000m show similar trends to those observed for the marathon (figures 1 and 2; table II). Sprinting performances (100–400m) also stabilised for women in the late 1980s (figure 3), and present-day sex differences are similar to those for distance running (7–10%) [table II]. These percentage differences between the sexes (~10%) are often perceived as 'small'. However, the prediction that women will not break the 4-minute-mile barrier until 2033,^[16] almost 80 years after Roger Bannister accomplished the same historic feat, provides reference for the true magnitude of these differences. More recent non-linear curve models^[17] suggest that women will never match Roger Bannister's best. In agreement, even 'ultimate' performance projections for women at 100m show them never eclipsing the 10-second milestone.^[16] Importantly, the model used to make future predictions applies physiological parameters

(anaerobic power, aerobic power, and endurance capability or fractional utilisation of aerobic power) to calculate performance potential, rather than purely mathematical data treatment.^[6-8,17] The model, now >15 years old, was very close to reality for world bests in 2000. Current performance advantages retained by men over women in running events from 100 to 42 000m (table II) appear best explained by biological sex differences.

2. Explaining the Differences

2.1 Distance Running

Although societal influences (sports participation and training) probably made the largest historical impact,^[2,9,10,15,18] the differences in aerobic fitness between the sexes narrowed markedly as classic analyses like that of Sparling^[19] demonstrated the importance of expressing oxygen uptake relative to body mass when comparing men and women on aerobic power parameters. Yet even when the contribution of body fat to sex differences in aerobic capacity is controlled and maximal oxygen uptake ($\dot{V}O_{2max}$) is expressed relative to lean body mass, men still retain a considerable aerobic performance advantage.^[1,18,20]

Physiological determinants of aerobic running performance are often explained using a classic three-tiered model that includes maximal aerobic power, lactate threshold and economy of movement.^[21] Together these three variables determine how long a runner can sustain a given exercise power output. According to Peronnet and Thibault,^[16] a linear increase in $\dot{V}O_{2max}$ best explains progressive distance running improvements in both men and women, since the fractional utilisation of oxygen remains unchanged over time,^[16] and sex differences in running economy and lactate threshold have not been established.^[9,22]

More than 10 years ago, mathematical modelling of marathon performance predicted times for the

year 2000 in men (335 m/min) and women (302.8 m/min) very close to actual outcomes (men 334 m/min; women 298.5 m/min).^[3,16] These predictions took into account an ~10% difference in $\dot{V}O_{2\max}$ (mL/kg/min) for elite men and women attributable to biological differences in body composition, cardiovascular preload and blood oxygen-carrying capacity.^[1,10,15,22,23] This consistent ~10% performance edge is retained by men across endurance running events from 1500 to 42 000m (table II). A more detailed discussion of these physiological differences between men and women and how they relate to distance running performance can be found elsewhere.^[1,9,15,18-20,22]

The idea that differences in running performance between men and women should progressively narrow as a function of racing distance was first voiced in 1962.^[2] Yet table II indicates a consistent ~10% performance difference between the sexes from 1500 to 42 000m. Some^[11,13] suggest that women might outrun men at distances beyond 42 000m, but this is not observed for individual world records between 100 and 200km.^[9,12] Similarly, records for men are faster (~25%) than those for women at even longer distances (up to 1000km)^[1] when races are contended on a certified track, thus removing some of the inherent bias associated with differences in cross-country courses. Those suggesting that women might be superior runners at distances beyond 42 000m^[11,13] have matched the sexes for aerobic power in their comparisons. This is a sound scientific practice, but not the usual competitive condition.^[1,10,15,22] The additional impact that anthropometric, thermoregulatory and metabolic differences between men and women can have on distance running performance is also of interest and has been reviewed in detail elsewhere.^[1,5,9,15,22,24-27] However, a future intersection in endurance running performance times between men and women seems unlikely in the absence of true biological changes that ultimately equate men and women on $\dot{V}O_{2\max}$.^[16,28,29]

2.2 Sprint Running

Sex differences in sprint running have received very limited attention^[9] compared with distance running, despite the fact that the smallest performance difference between men and women is actually observed at 100m (7.3%) [table II]. Sprint speed is most simply defined as the product of stride length and stride frequency.^[30] Faster sprint performances for men compared with women must therefore be the result of longer strides, more frequent strides, or both. In an elegant study^[30] comparing these elements in runners with top sprinting speeds ranging from 360 to 600 m/min, it was concluded that the repositioning of limbs (stride frequency) was similar in fast and slower runners, but faster runners applied greater ground forces,^[30] resulting in faster top speeds by virtue of longer strides.^[30-32]

How do faster runners generate greater ground forces? Weyand et al.^[30] suggest that the greater force-producing capacity is attributable to greater power-output potential of fast twitch muscle fibre. While athletes who excel in explosive sports do possess more fast twitch muscle fibres,^[33] similar fibre type distributions between men and women have been reported for track athletes,^[34] as well as other athlete populations.^[33,35-37] Although many structural characteristics of muscle can potentially contribute to force production and running speed (fibre type, fibre length, pennation angle, fascicle length), only muscle fibre cross-sectional area (CSA) differs between men and women.^[35,37-40] Strength is known to correlate positively with both muscle CSA^[41] and sprint speed.^[42] Although strength is similar between the sexes when expressed relative to muscle CSA,^[38,43] men still display greater absolute strength than women because strength is proportional to skeletal muscle mass,^[44] of which men have more.^[45] Higher concentrations of circulating testosterone in men than in women and its effects on skeletal muscle protein synthesis^[46-48] probably explain this physiological differ-

ence in CSA. Circulating testosterone results in more muscle mass and larger muscle CSAs that translate into superior ground forces, thus resulting in superior sprinting performances for men. Like those of distance running, sprinting performances between the sexes are unlikely to narrow naturally in the absence of changes in these biological factors.

3. Performance Differences: the Future?

As a result of important biological equation parameters, model predictions suggest that men will continue to outperform women in the marathon and other running events by ~10% well into the future^[16] (figures 1–3). But could these parameters be altered? The use of performance-enhancing drugs among women is reportedly on the rise,^[49] and it is arguable that some women's records were achieved with ergogenic drugs, based upon legitimate *post hoc* use documents.^[9] At the same time, it is equally or more probable, based on use numbers,^[49] that many current records for men were also achieved with drug use, making this factor sex equitable with respect to future performance gaps. Interestingly, a more extreme, but fair, enhancement in strength and endurance could also influence model predictions for the future.

The Executive Board of the International Olympic Committee (IOC), in response to an IOC Medical Commission proposal, will now allow athletes undergoing sexual re-assignment surgery to compete in their re-assigned sex category whether re-assigned before or after puberty.^[50] The IOC reports that transsexual competitors are rare, but becoming more common, thus requiring an official policy. Although hormone suppression therapy or the removal of gonads suppresses the advantages conferred by testosterone, neither treatment fully reverses it.^[48] The story of Richard Raskind's (Renee Richards) US Open tennis success after male-to-female sexual re-assignment surgery is a well pub-

licised example.^[51] It therefore remains conceivable that males re-assigned as females after puberty could retain a significant advantage (i.e. more lean body mass)^[48] over athletes born women in events like sprinting, as well as for running events requiring a high $\dot{V}O_{2\max}$. Figure 4 illustrates that even the 100th fastest 1500 and 42 000m times for men in 1996 were faster than the world's best women's times at those distances for the same year. Might one man seek a potential gold medal through sexual re-assignment where no medal was once possible? Only the future will tell if this new policy will influence the performance gap between the sexes.

4. Conclusion

Similar plateaus in running performance for men and women over the past 20 years reflect growing sex equality in sports participation. Models of performance corroborate this assertion, showing improved prediction accuracy after 1975,^[16] coinciding roughly with Title IX legislation in the US and the drastic increase in women's sports participation in the former Eastern block. Present-day sex differences in running performance appear to be of biological origin. Men possess greater muscular strength and a larger aerobic capacity. As a result, the gap in running performance between men and women is unlikely to narrow naturally.

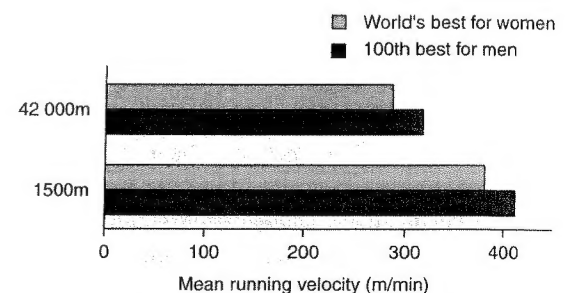


Fig. 4. Comparison of mean running velocities at 1500 and 42 000m for the world's fastest times for women and 100th fastest times for men in 1996.^[10]

Acknowledgements

The authors wish to thank Bryant Stamford, PhD, University of Louisville, Lynn Panton, PhD, Florida State University, and Krista Austin, PhD, Florida State University, for reading and remarking on this manuscript. The views, opinions and/or findings contained in this report are those of the authors and should not be construed as an official Department of the Army position, or decision, unless so designated by other official documentation. Approved for public release; distribution unlimited.

No sources of funding were used to assist in the preparation of this review. The authors have no conflicts of interest that are directly relevant to the content of this review.

Appendix

For all events from 100 to 10 000m, only times officially recognised by the International Association of Athletics Federations (IAAF)^[3,4] have been included. Marathon records are technically 'unofficial', since the IAAF does not recognise records not made on a track. Two published women's records for the marathon (1926 and 1963) are not depicted because of questions surrounding race distance authenticity. For 100–400m, only electronic times were considered. Both electronic and hand timing rounded to the nearest 0.10 seconds have been included for 1500–42 000m, where performance margins are wider. Since 1981, all events from 100 to 10 000m are recorded to the nearest 0.01 second. No distinction has been made between records set at altitude or at sea level, but all records represent outdoor bests. For graphic presentation, only the single fastest time recorded in any given year is reported even if a record was broken more than once that year. A record is then depicted repeatedly in subsequent years until a new record was set. Predictions for 2028 are from Peronnet and Thibault.^[16]

References

1. Cheuvront SN, Moffatt RJ, DeRuisseau K. Body composition and gender differences in performance. In: Driskell JA, Wolinsky I, editors. *Nutritional assessment of athletes*. Boca Raton (FL): CRC Press, 2002: 177-200
2. Kuscsik N. The history of women's participation in the marathon. *Ann N Y Acad Sci* 1977; 301: 862-76
3. Hymans R. Progression of world best performances and IAAF official world records. 5th ed. Monaco (FR): International Association of Athletics Federations, 2003
4. International Association of Athletics Federation (IAAF) statistics [online]. Available from URL: <http://www.iaaf.org/statistics/index.html> [Accessed 2004 May]
5. Cheuvront SN, Haymes EM. Thermoregulation and marathon running: biological and environmental influences. *Sports Med* 2001; 31 (10): 743-62
6. Whipp BJ, Ward SA. Will women soon outrun men? [letter]. *Nature* 1992; 355 (6355): 25
7. Tatem AJ, Guerra CA, Atkinson PM, et al. Momentous sprint at the 2156 Olympics? *Nature* 2004; 431: 525
8. Ryder HW, Carr HJ, Herget P. Future performance in footracing. *Sci Am* 1976; 234: 108-19
9. Noakes TD. *Lore of running*. 4th ed. Champaign (IL): Leisure Press, 2003
10. Sparling PB, O'Donnell EM, Snow TK. The gender difference in distance running performance has plateaued: an analysis of world rankings from 1980 to 1996. *Med Sci Sports Exerc* 1998; 30 (12): 1725-9
11. Bam J, Noakes TD, Juritz J, et al. Could women outrun men in ultramarathon races? *Med Sci Sports Exerc* 1997; 29 (2): 244-7
12. Coast JR, Blevins JS, Wilson BA. Do gender differences in running performance disappear with distance? *Can J Appl Physiol* 2004; 29 (2): 139-45
13. Speechly DP, Taylor SR, Rogers GG. Differences in ultra-endurance exercise in performance-matched male and female runners. *Med Sci Sports Exerc* 1996; 28 (3): 359-65
14. Holden C. An everlasting gender gap? *Science* 2004; 305 (5684): 639-40
15. Sparling PB, Nieman DC, O'Connor PJ. Selected scientific aspects of marathon racing: an update on fluid replacement, immune function, psychological factors and the gender difference. *Sports Med* 1993; 15 (2): 116-32
16. Peronnet F, Thibault G. Mathematical analysis of running performance and world running records. *J Appl Physiol* 1989; 67 (1): 453-65
17. Nevill AM, Whyte G. Are there limits to running world records? *Med Sci Sports Exerc* 2005; 37: 1785-8
18. Drinkwater BL. Women and exercise: physiological aspects. *Exerc Sport Sci Rev* 1984; 12: 21-51
19. Sparling PB. A meta-analysis of studies comparing maximal oxygen uptake in men and women. *Res Q Exerc Sport* 1980; 51 (3): 542-52
20. Sparling PB, Cureton KJ. Biological determinants of the sex difference in 12-min run performance. *Med Sci Sports Exerc* 1983; 15 (3): 218-23
21. Pate RR, Branch JD. Training for endurance sport. *Med Sci Sports Exerc* 1992; 24 (9 Suppl.): S340-3
22. Joyner MJ. Physiological limiting factors and distance running: influence of gender and age on record performances. *Exerc Sport Sci Rev* 1993; 21: 103-33
23. Cureton K, Bishop P, Hutchinson P, et al. Sex difference in maximal oxygen uptake: effect of equating haemoglobin con-

- centration. *Eur J Appl Physiol Occup Physiol* 1986; 54 (6): 656-60
24. Ruby BC, Robergs RA. Gender differences in substrate utilisation during exercise. *Sports Med* 1994; 17 (6): 393-410
 25. Dennis SC, Noakes TD. Advantages of a smaller bodymass in humans when distance-running in warm, humid conditions. *Eur J Appl Physiol Occup Physiol* 1999; 79 (3): 280-4
 26. Dotan R, Rotstein A, Dlin R, et al. Relationship of marathon running to physiological, anthropometric and training indices. *Eur J Appl Physiol Occup Physiol* 1983; 51: 281-93
 27. Wells CL, Hecht LH, Krahenbuhl GS. Physical characteristics and oxygen utilization of male and female marathon runners. *Res Q Exerc Sport* 1981; 52 (2): 281-5
 28. Davies CT, Thompson MW. Aerobic performance of female marathon and male ultramarathon athletes. *Eur J Appl Physiol Occup Physiol* 1979; 41 (4): 233-45
 29. Maughan RJ, Leiper JB. Aerobic capacity and fractional utilisation of aerobic capacity in elite and non-elite male and female marathon runners. *Eur J Appl Physiol Occup Physiol* 1983; 52 (1): 80-7
 30. Weyand PG, Sternlight DB, Bellizzi MJ, et al. Faster top running speeds are achieved with greater ground forces not more rapid leg movements. *J Appl Physiol* 2000; 89 (5): 1991-9
 31. Cavagna GA, Kaneko M. Mechanical work and efficiency in level walking and running. *J Physiol* 1977; 268 (2): 467-81
 32. Armstrong LE, Cooksey SM. Biomechanical changes in selected collegiate sprinters due to increased velocity. *Track Field Q Rev* 1983; 3: 10-2
 33. Prince FP, Hikida RS, Hagerman FC. Human muscle fiber types in power lifters, distance runners and untrained subjects. *Pflugers Arch* 1976; 363 (1): 19-26
 34. Costill DL, Daniels J, Evans W, et al. Skeletal muscle enzymes and fiber composition in male and female track athletes. *J Appl Physiol* 1976; 40 (2): 149-54
 35. Alway SE, Grumbt WH, Gonyea WJ, et al. Contrasts in muscle and myofibers of elite male and female bodybuilders. *J Appl Physiol* 1989; 67 (1): 24-31
 36. Sale DG, MacDougall JD, Alway SE, et al. Voluntary strength and muscle characteristics in untrained men and women and male bodybuilders. *J Appl Physiol* 1987; 62 (5): 1786-93
 37. Schantz P, Randall-Fox E, Hutchison W, et al. Muscle fibre type distribution, muscle cross-sectional area and maximal voluntary strength in humans. *Acta Physiol Scand* 1983; 117 (2): 219-26
 38. Miller AE, MacDougall JD, Tarnopolsky MA, et al. Gender differences in strength and muscle fiber characteristics. *Eur J Appl Physiol Occup Physiol* 1993; 66 (3): 254-62
 39. Abe T, Brechue WF, Fujita S, et al. Gender differences in FFM accumulation and architectural characteristics of muscle. *Med Sci Sports Exerc* 1998; 30 (7): 1066-70
 40. Abe T, Fukashiro S, Harada Y, et al. Relationship between sprint performance and muscle fascicle length in female sprinters. *J Physiol Anthropol Appl Human Sci* 2001; 20 (2): 141-7
 41. Tesch P, Karlsson J. Isometric strength performance and muscle fibre type distribution in man. *Acta Physiol Scand* 1978; 103 (1): 47-51
 42. Alexander MJ. The relationship between muscle strength and sprint kinematics in elite sprinters. *Can J Sport Sci* 1989; 14 (3): 148-57
 43. Komi PV, Karlsson J. Skeletal muscle fibre types, enzyme activities and physical performance in young males and females. *Acta Physiol Scand* 1978; 103 (2): 210-8
 44. Ford LE, Dettlerline AJ, Ho KK, et al. Gender- and height-related limits of muscle strength in world weightlifting champions. *J Appl Physiol* 2000; 89 (3): 1061-4
 45. Wilmore J, Costill DL. Growth, development, and the young athlete. In: *Physiology of sport and exercise*. 2nd ed. Champaign (IL): Human Kinetics, 1999: 516-35
 46. Herbst KL, Bhasin S. Testosterone action on skeletal muscle. *Curr Opin Clin Nutr Metab Care* 2004; 7 (3): 271-7
 47. Willoughby DS, Taylor L. Effects of sequential bouts of resistance exercise on androgen receptor expression. *Med Sci Sports Exerc* 2004; 36 (9): 1499-506
 48. Gooren LJ, Bunck MC. Transsexuals and competitive sports. *Eur J Endocrinol* 2004; 151 (4): 425-9
 49. Bahrke MS, Yesalis CE. Abuse of anabolic androgenic steroids and related substances in sport and exercise. *Curr Opin Pharmacol* 2004; 4 (6): 614-20
 50. IOC approves consensus with regard to athletes who have changed sex [online]. Available from URL: http://www.olympic.org/uk/includes/common/article_print_uk.asp?id=841 [Accessed 2004 May]
 51. Fee E, Brown TM, Laylor J. One size does not fit all in the transgender community. *Am J Public Health* 2003; 93 (6): 899-900

Correspondence and offprints: Dr Samuel N. Cheuvront, US Army Research Institute of Environmental Medicine, Natick, MA 01760-5007, USA.
E-mail: Samuel.cheuvront@na.amedd.army.mil